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LCA OF WASTE MANAGEMENT SYSTEMS

Life cycle impact assessment and interpretation of municipal solid waste management scenarios based on the midpoint and endpoint approaches

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Abstract

Purpose Few studies have examined differing interpretations of life cycle impact assessment (LCIA) results between midpoints and endpoints for the same systems. This paper focuses on the LCIA of municipal solid waste (MSW) systems by taking both the midpoint and endpoint approaches and uses LIME (Life Cycle Impact Assessment Method based on Endpoint Modeling, version 2006). With respect to global and site-dependent factors, environmental impact categories were divided into global, regional, and local scales. Results are shown as net emissions consisting of system emissions and avoided emissions.

Materials and methods This study is divided into five segments. The first segment develops the LCIA framework and four MSW scenarios based on the current MSW composition and systems of Seoul, considering adaptable results from the hierarchy MSW systems. In addition, two systems are considered: main MSW systems and optional systems. Several "what if" scenarios are discussed, including various compositions and classifications of MSW. In the second segment, life cycle inventory (LCI) analysis is applied to define various inputs and outputs to and from MSW systems, including air (23 categories), water (28 categories) and land (waste) emissions, resource consumption, land use, recovered material, compost, landfill gas, biogas, and heat energy. The third segment, taking the midpoint approach, investigates the nine environmental impacts of the system and avoided emissions. In the fourth segment, this study, taking the endpoint approach, evaluates the damages, dividing the four safeguard subjects affected by 11 environmental impact categories of the system and avoided emissions. In these third and fourth segments, LCIA is applied to analyze various end-of-life scenarios for same MSW materials. The final segment defines the differences from the results in accordance with the two previous life cycle assessment methodologies (the LCIA and interpretations with respect to midpoints and endpoints).

Results and discussion With the respect to midpoints, Scenario 1 (S1) using 100% landfills (L) is the worst performer in terms of global (global warming and resource consumption), regional (acidification, human toxicity, and ecotoxicity), and local (waste: landfill volume) impacts. In terms of all impacts except global warming and waste, Scenario 2 (S2) using 64.2% L and 35.8% material recycling (MR) was found to be the most effective system. With respect to global-scale endpoints, S1 was the worst performer in terms of human health and social assets, whereas the other scenarios with MR were poor and bad performers in terms of biodiversity and primary production. With respect to regional- and local-scale endpoints, S1 was the worst performer in terms of human health, biodiversity, and primary production, whereas Scenario 4 (S4) using 4.2% L (only incombustibles), 35.8% MR, 28.5% biological treatment (BT), and 31.5% incineration (I) was the worst performer in terms of social assets. S4 was the best performer in terms of global-scale endpoints, whereas S2 and Scenario 3 (S3, using 35.7% L, 35.8% MR, and 28.5%

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BT) were the best on regional- and local-scale endpoints, respectively. With respect to the monetization analysis, which considered net emissions and integrated all endpoints, S3 was found to be "the most effective system," indicating US $31.6 savings per ton-waste.

Conclusions The results of this study illustrate the differences in the LCIA outcomes and interpretations with respect to the midpoint and endpoint approaches. In addition, it would be possible to interpret the effect of each indicator on safeguard subjects by integrating separate midpoints. The LCIA results of each endpoint for the scenarios were generally consistent with those of each midpoint. However, the results changed dramatically when the main contributor was a new category not included in midpoint categories. The key advantage with respect to grouping impact categories in the midpoint and endpoint approaches can be described as "the simplification of midpoints and the segmentation of endpoints."

Recommendations and perspectives This research raises many questions that warrant further research. This method does not provide an uncertainty evaluation of input data at the inventory level; it addresses only the main contributor for each impact category to four endpoints. In addition, it would be beneficial to investigate the suitability of midpoints and endpoints for different stakeholders with a low or high level of environmental expertise by comparing previous studies.

Keywords Damage potential · Environmental impact assessment · Grouping environmental impacts · LCIA · MSW management scenario · Municipal solid waste

1 Background, aim, and scope

1.1 Schematic interpretation of relationships between midpoint and endpoint approaches

Recent studies on life cycle impact assessment (LCIA) have attempted to establish a linkage between midpoints and endpoints (Bare et al. 2000; Hertwich and Hammitt 2001; Jolliet et al. 2003; Itsubo and Inaba 2003; Jolliet et al. 2004; Finnveden et al. 2006) and a comprehensive impact assessment taxonomy (Pennington et al. 2004; Bare and Gloria 2007). The midpoint approach (e.g., Heijungs et al. 1992, Eco-indicator 95: Goedkoop 1995, EDIP: Hauschild and Wenzel 1998 and further adaptations, CML2 baseline method 2000, The Dutch Handbook: Guinée et al. 2002, and TRACI: Bare et al. 2003) for characterization with mandatory elements (ISO 14042) is a typical method, even if it provides a dozen or so impact category indicator results (Bare et al. 2000; Jolliet et al. 2004). The endpoint approach (e.g., Steen and Ryding 1992, ExternE 1998, ESEERCO 1995, EPS: Steen 1999, and Eco-indicator 99: Goedkoop and Spriensma 2001) has simple and easily understandable damage categories (expressed as "safeguard subject," introduced by Steen and Ryding 1992), providing results with a lower level of interpretive uncertainty in comparison to the midpoint approach (Bare et al. 2000; Jolliet et al. 2004; Heijungs et al. 2003).

LIME (Life Cycle Impact Assessment Method based on Endpoint Modeling), developed by the LCA Japan Forum (2006), is a damage-oriented LCIA method for qualifying environmental impacts of environmental loading in Japan as accurately and transparently as possible. LIME, which is different from other methods in terms of the ways in which midpoint and endpoint approaches are applied, includes three factors applicable to the LCIA method: (1) characterization, (2) damage assessment, and (3) weighting. LIME includes two types of weighting steps: the aggregation of indicator results across impact categories to safeguard subjects and across safeguard subjects into a single index. The public is provided with conversion factors associated with midpoints and endpoints in LIME for 1,000 types of substances and 80 types of land use (refer to Table 1, Steen 1999; Goedkoop and Spriensma 2001; Itsubo and Inaba 2005).

More recent arguments against the two approaches have been characterized mainly by their mechanisms and interpretations. Bare (2005) proposed that the midpoint analysis is more inclusive of endpoint effects, increasing the comprehensiveness of impacts. On the other hand, even if two systems such as nuclear energy and fossil fuels have completely different impact pathways (cause–effect mechanisms), the two systems can be compared by the endpoint approach (Lenzen 2006). In addition to the double counting of damages, there is another problem with this approach: it fails to take all potential damages into account, estimating only characterized damages that have been clearly defined. With respect to the interpretations of LCIA results, midpoints can be very useful in the provision of information to stakeholders that do not want uncertain endpoint indicator results (Heijungs et al. 2003; Lenzen 2006). Bare et al. (2000) suggested that there are advantages and disadvantages to each approach and that a combination of these approaches may provide more information than just the typical ensemble of midpoint indicator results.

However, there has been little discussion about the differing interpretations of LCIA results between midpoints and endpoints for the same systems. In this regard, this study assumes that decision makers could benefit by basing their judgments on different perspectives of the midpoint and endpoint approaches—for example, perspectives provided through assessment methods that are divided into environmental impact categories (midpoints) and damage categories (endpoints).

Table 1 A comparison of various endpoint methods

Method	LIME (version 2006)	Eco-indicator 99 (version 2000)	EPS (version 2000)	ExternE (version 1998)
Structure of assessment	Inventory >> Characterization >> Endpoint effects >> Safeguard subjects >> Single index (conjoint analysis and the AHP)	Inventory >> Safeguard subjects >> Normalization >> Single index (a panel procedure)	Inventory >>Endpoint effects >>Single index (market price: the WTP; non-market environmental values: the CVM)	Inventory >> Endpoint effects >> Single index (the CVM)
Inventory	1,000 substances and 80 types of land use	550 substances and 10 types of land use	250 substances and 5 types of land use	13 substances
Impact categories	Global warming, ozone-layer depletion, resource consumption, acidification, human toxicity, eco-toxicity, eutrophication, photochemical oxidant creation, waste, urban air pollution, and land use	Climate change, ozone-layer depletion, resource consumption, eco-toxicity, acidification, eutrophication, ionized radiation, respiratory effects, carcinogenesis, and land use	–	–
Conversion factors	Characterization, damage, normalization (monetary values), and weighting factors	Damage and normalized damage, weighted damage, normalization (dimensionless), and weighting factors	Damage and weighting (damage cost) factors	Damage and weighting (damage cost) factors
Type of safeguard subjects	Damage to human health, social assets, biodiversity, and primary production	Damage to human health, ecosystem quality, and mineral and fossil resources	Damages to human health, ecosystem production capacity, abiotic stock resources (natural resources), biodiversity, and cultural and recreational value (esthetic value)	External costs of energy conversion from negative impacts on human health, crop losses, material damage, and global warming
Target area/ Sample size	Japan/A sample of 400 participants through interviews	EU/A sample of 80 participants by mail (a 20% return rate)	Sweden/–	EU/–

Recently, there has been some debate about the prioritization of the waste hierarchy (reuse–reduce–material recovery/biological treatment–incineration/landfill). Energy and material recovery from municipal solid waste (MSW) can vary according to characteristics and systems of MSW (Yi et al. 2007) and influence the prioritization of MSW management. If the MSW scenarios (Scenarios 1, 2, 3, and 4) were developed based on the waste hierarchy, further, it may be possible to prioritize MSW management by comparing environmental impacts under Scenarios 1, 2, 3, and 4.

1.2 Aim and scope

This study evaluates various MSW management scenarios (based on current MSW systems in Seoul) through the midpoint and endpoint approaches with respect to LCIA and defines the differences by interpreting the midpoint and endpoint LCIA results according to global, regional, and local spatial scales. LIME (version 2006) was selected as the assessment tool for the current study.

In the interpretation of LCIA for MSW management, the performance of global, regional, and local impacts and avoided impacts such as energy and resource savings is an important key factor. As one possible way to group LCIA results (Volkwein et al. 1996; Giegrich and Schmitz 1996; Schmitz and Paulini 1999), this study introduces sorting impact categories based on associated endpoints to facilitate the interpretation of the results into specific areas of concern.

This study conducts no uncertainty analysis for the estimation of the uncertainty of input data because it uses background data (i.e., IWM-1 and IWM-2 Life Cycle Inventory models, White et al. 1999; McDougall et al. 2009) for research purposes, which involve a comparison of the prioritization of scenarios between the approaches, not an evaluation of precise LCA results. Furthermore, this study conducts no sensitive analysis using minimum and maximum values indicated in previous research because the study assumes that the background data indicate default values, which has been verified by a number of previous studies. Because this study estimates 51 emission categories by considering energy consumption and generation and 9 MSW treatment/disposal/recovery options, both of these analysis methods would not have been appropriate.

2 Materials and methods

2.1 Development of the LCIA framework

In this study, the elements of LCIA were modified as shown in Table 2. Normalization and weighting (integration) steps were excluded in the midpoint approach. As the integration step, a monetization analysis was carried out to integrate all endpoints. Furthermore, the original grouping based on impact spatial scales (e.g., site-dependent midpoint factors and the exposure and damage according to the distance from the emission source, Potting et al. 1998a, b; UNEP 2003; Curran 2006) was adapted.

Previous studies, regardless of the approach used (midpoint or endpoint), have suffered from serious limitations in defining the exact environmental impact potential from emissions. There is no clear evidence that certain chemicals cause damage to human health and the environment. The environmental impact and damage potential (adapted from LIME model, version 2006) of emission categories (adapted from IWM-1 and IWM-2 models) were defined through the midpoint and endpoint approaches of this study (Fig. 1).

LIME was selected to best reflect the Seoul environment with respect to conversion factors because LIME was developed as a Japanese version (except for the global warming, ozone-layer depletion, and resource consumption categories), which are applicable to the Asian environment. Furthermore, LIME is used to evaluate simultaneously midpoints and endpoints derived from environmental impact categories. The scenarios of this study can be used to assess overall environmental impacts by using global, country-dependent, and city-dependant characterization factors in LIME. The safeguard subjects of LIME would be considerably susceptible to geological and physical conditions; therefore, the results of LCIA need to be interpreted with caution.

The midpoint results from nine impact categories were interpreted by grouping global (global warming, ozone-layer depletion, and resource consumption), regional (acidification, human toxicity, ecotoxicity, and eutrophication), and local (photochemical oxidant and waste) impacts, not including urban air pollution and land use. Endpoints such as human health, social assets, biodiversity, and primary production derived from 11 environmental impact categories were also evaluated by grouping damages from global, regional, and local impacts.

Normalization factors (i.e., monetization factors, monetary values in units of Japanese Yen) can also be used with the LIME model, indicating economic valuation. This is useful for comparing two MSW systems with conflicting damage indicators (for example, System A was higher on human health and System B was higher on biodiversity). In this case, the outcome would depend on the monetization factors for the four safeguard subjects. This analysis did not include the weighting factors to a single index (conjoint analysis: human health 0.31, social assets 0.17, biodiversity 0.25, and primary production 0.27 and AHP: human health 0.40, social assets 0.13, biodiversity 0.25, and primary production 0.22) provided by the LIME model, which are

Table 2 LCIA element selection with respect to midpoint and endpoint approaches

LCIA elements	Midpoint	Endpoint
1. Selection and definition of impact categories	9 impact categories	11 impact categories
2. Classification		
3. Characterization	9 midpoints	4 endpoints
4. Normalization	X	O
5. Integration	X	O
6. Grouping	Global/regional/local spatial scales	Global/regional/local spatial scales
7. Evaluating and reporting LCIA results	O	O
8. Interpretations	O	O

Elements numbered 1, 2, and 3 are mandatory elements, and 4, 5, and 6 optional elements of LCIA

the amounts the Japanese would be willing to pay for damage categories (Itsubo and Inaba 2003). These weighting factors may vary according to the population or stakeholders in that they can have different values for culture, economics, the environment, and education, among others (Itsubo et al. 2000). Any evaluation using these weighting factors, which may lead to large differences when integrating LCA results, should be implemented with caution. Thus, this study considers only monetary factors for integrating results for estimated damage.

From the indirect environmental impact point of view, potential impacts were estimated in terms of nonfossil CO_2 (otherwise known as biogenic CO_2) equivalent emitted and the MJ of energy equivalent. IPCC greenhouse gas (GHG) emission inventories exclude nonfossil CO_2 emissions from the assessment of global warming potential (GWP) and the macroscale (i.e., global) study of climate change. The climate, however, responds equally to fossil and nonfossil CO_2 (Finnveden et al. 2000); thus, all GHG emissions (Table 3), whether fossil or nonfossil in origin, associated with the waste stream were considered for this study's microscale (i.e., regional) comparison of MSW systems.

This study introduces the two types of source-oriented environmental impacts or damages through both midpoint

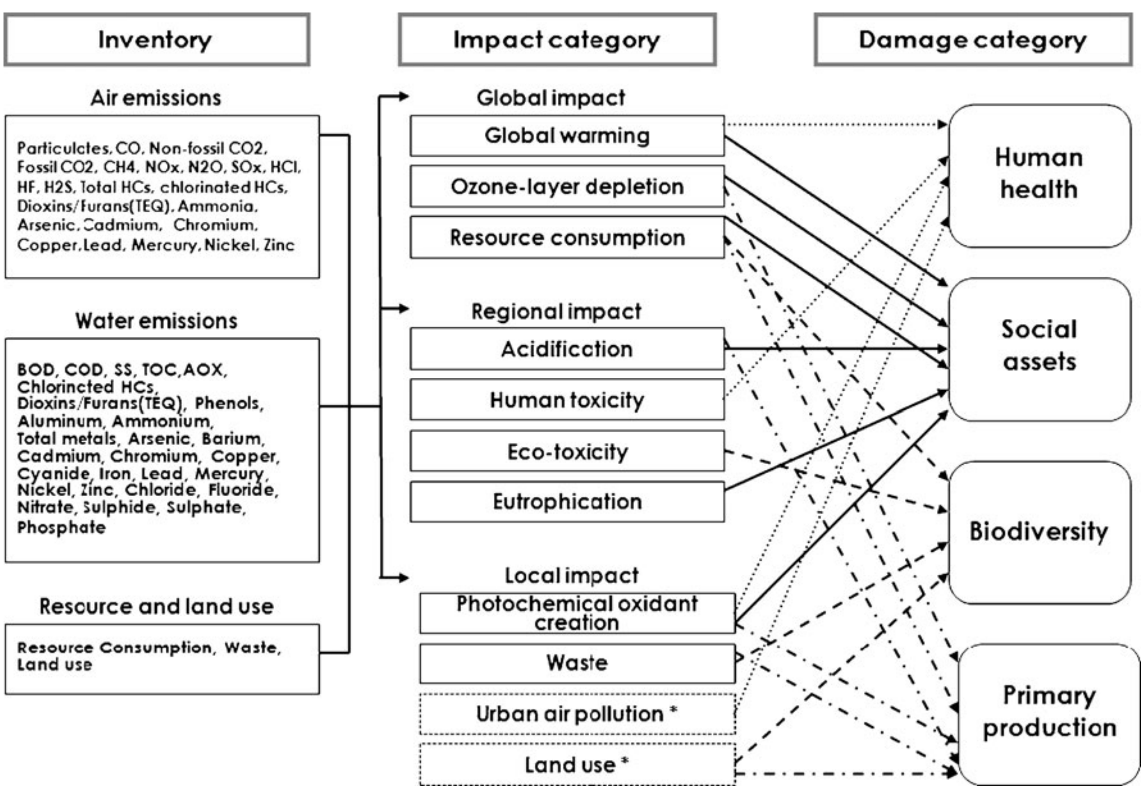


Fig. 1 Holistic structure of the LCIA framework at midpoints and endpoints (*not included in the midpoint results)

Table 3 Major greenhouse gases after taking into account global sink ability

	Greenhouse gases	Anthropogenic sources
Non-GWP	Nonfossil CO_2	Biodegradable waste combustion, waste dumps, compost, and biogasification
GWP	Fossil CO_2	Fossil origin waste combustion and fossil-fuel combustion
	Methane	Waste dumps and fossil-fuel combustion
	Nitrous Oxide	Fertilizer and fossil-fuel combustion

and endpoint approaches. Thus, LCIA results are shown as "Net emissions," indicating "System emissions from each scenario" minus "Avoided emissions from the use of the energy and material outputs from that scenario." System emissions included overall emissions from energy consumption, waste processes, and waste combustion. Avoided emissions included all emissions from energy consumption and virgin material processes (not including resource savings and inherent energy of feedstock materials).

2.2 Scenario development

Table 4 illustrates four scenarios composed of main and optional systems, which consider hierarchical MSW systems based on the current composition of MSW in Seoul and on the city's existing MSW systems. The composition of mixed waste in landfill processes differed for Scenarios 1, 2, 3, and 4 (S1, S2, S3, and S4, respectively). The main systems of MSW management in this study were landfill (L), material recycling (MR), biological treatment (BT), and incineration (I). Optional systems for assessing avoided impacts were divided into energy and material recoveries. In particular, these scenarios were designed to define avoided effects through the use of optional systems. Energy recovery involved landfill gas (LFG) recovery from L, heat energy recovery from I, and biogas recovery from the biogasification of food waste (BT). Material recovery involved materials recovered from reprocessing processes (MR) and compost from food waste (BT). This research analyzes, from the electricity and district heating system perspectives, environmental impacts of avoided emissions, which refers to the use of combined heat and power (CHP) from waste. The avoided impact of material recovery was assessed by calculating the virgin material use and chemical fertilizer production.

The actual categories of MSW materials collected in Seoul (Yi et al. 2011) were reclassified and combined to those of waste inputs based on the life cycle inventory (LCI). Mixed waste in landfill processes was classified into paper (29.3% in S1, 10.9% in S2 and S3, and 0% in S4), glass (5.5% in S1 and 0% in S2, S3, and S4), steel (8.1% in S1 and 0% in S2, S3, and S4), aluminum (0.8% in S1 and 0% in S2, S3, and S4), plastics (6.5% in S1, 3.5% in S2 and S3, and 0% in S4), food waste (28.5% in S1 and S2, and 0% in S3 and S4), wood and other combustibles (14.5% in S1, S2, and S3 and 0% in S4), rubber (2.5% in S1, S2, and S3 and 0% in S4), and incombustibles (4.2% in S1, S2, S3, and S4), based on their components (particularly the organic fraction) and LFG generation. Biodegradable fractions such as paper, food waste, wood, and other combustibles in landfill processes under each scenario generate landfill gas. After excluding recyclables in S2, the biodegradable fraction increased to 84% of mixed waste, whereas those of S1 and S3 were 72% and 71%, respectively.

Recyclable items were divided into paper (18.4% in S2, S3, and S4), glass (5.5% in S2, S3, and S4), steel (6.7% in S2, S3, and S4), aluminum (2.2% in S2, S3, and S4),

Table 4 Main and optional system scenarios

	Main system				Optional system	Avoided impact
	L	MR	BT	I		
S1	100% Mixed waste + Recyclables + Food waste				A (50% LFG Recovery)	A (CHP plant)
S2	64.2% Mixed waste + Food waste	35.8% Recyclables			A + B (Reprocessing Process)	A + B (Virgin material)
S3	35.7% Mixed waste	35.8% Recyclables	28.5% Food waste		A + B + C (11.7% Composting, 16.8% Biogasification)	A + B + C (Fertilizer, CHP and fertilizer)
S4	4.2% Incombustible	35.8% Recyclables	28.5% Food waste	31.5% Mixed waste	B + C + D (Heat energy recovery)	B + C + D (CHP)

HDPE plastics (0.6% in S2, S3, and S4), and non-HDPE plastics (2.4% in S2, S3, and S4), based on their components and energy consumption. The steel category included scrap iron and steel cans. Because steel cans account for approximately 65% of total cans in Seoul (Seoul Environment Bureau 2006), the remainder was assumed to be aluminum for the purpose of this study. According to the BUWAL (1998) report, rigid plastics have emissions and costs that are different from plastic films in the reprocessing and incineration processes. In this regard, based on a previous study (Seoul Environment Bureau 2006), this study assumed 20% rigid plastics (i.e., HDPE) and 80% plastic films (i.e., non-HDPE, including LDPE, PP, PET, PS, ABS, PSP, EPS, PVC, and other plastic materials).

The Seoul Development Institute (SDI) determined that 41% of food residuals in Seoul were due to the total food waste of the business sector and the remaining 59%, the residential sector (Yoo and Yi 2001). For the analysis of biological treatment processes, food residuals from the business and residential sectors were assumed to be carried into composting and biogasification processes, respectively.

Mixed waste in the incineration process was classified into paper (10.9% in S4), glass (0% in S4), steel (0% in S4), aluminum (0% in S4), HDPE plastics (0.7% in S4), non-HDPE plastics (2.8% in S4), food waste (0% in S4), wood (3.8% in S4), rubber (2.5% in S4), and other combustibles (10.7% in S4), based on their components (particularly air emissions and lower heating values of waste combustion).

2.3 Goal definition and system boundary

This study compares MSW treatment and disposal options for assessment purposes. The functional unit is one ton of fractional "household waste" in MSW. The "household waste" included residential (household and small business) and commercial waste (generating waste more than 300 kg per day and excluding industrial waste). As mentioned in Section 2.2, based on a flow analysis of Seoul (4,077 thousand tons/year, Yoo and Yi 2007; Yi et al. 2011), the composition of input waste varies according to different treatment and disposal facilities (Table 5). Waste collection and transfer and new construction of systems were excluded because they do not significantly impact final results (Finnveden and Ekvall 1998; Björklund 2000; McDougall et al. 2009). It is assumed that "best available technology" employed by existing MSW facilities in Seoul was chosen for assessing impacts in the system boundary because emissions and energy consumption vary according to best available, average, and worst technologies.

3 Life cycle inventory preparation

3.1 Input and output factors

Inventories of energy consumption and recovery and emissions were adapted and recalculated from the IWM-1 and 2 models. Yi (2009) provided a detailed rationale for this method (i.e., the lists of LCI, refer to Table 6). The LCI of inputs was performed with respect to the MSW composition (see Table 5) and net energy consumption of

Table 5 MSW material by scenario (thousand tons/year)

	S1	S2	S3	S4
Landfill				
Subtotal	4,077	2,618	1,454	171
Paper	1,194	445	445	0
Glass	224	0	0	0
Steel	331	0		0
Aluminum	32	0	0	0
Plastics	267	143	143	0
Food waste	1,164	1,164	0	0
Wood and other combustibles	591	591	591	0
Rubber	103	103	103	0
Incombustibles	171	171	171	171
Material recovery				
Subtotal		1,459	1,459	1,459
Paper		749	749	749
Glass		224	224	224
Steel		272	272	272
Aluminum		90	90	90
Plastic—non-HDPE		99	99	99
Plastic—HDPE		25	25	25
Biological treatment				
Subtotal			1,164	1,164
Composting			477	477
Biogasification			687	687
Incineration				
Subtotal				1,283
Paper				445
Glass				0
Steel				0
Aluminum				0
Plastic—non-HDPE				115
Plastic—HDPE				29
Food waste				0
Wood				156
Rubber				103
Other combustibles				435
Total amount	4,077	4,077	4,077	4,077

Table 6 Input/output categories

MSW inputs and outputs
Mixed waste, recyclables, and food waste
Recovered materials and compost
Energy inputs and outputs
Energy consumption during landfill, material reprocessing process, virgin material production, biological treatment, and incineration
Energy generation and natural gas equivalent during landfill, biological treatment, and incineration
Air and water emissions
Energy and resource production and use
Electrical energy generation
Combined heat power generation
Landfill process (landfill gas and leachate)
Landfill gas combustion (air emissions)
Material reprocessing process
Virgin material production
Biological treatment process (biogasification and composting)
Biogas combustion (air emissions)
Chemical fertilizer process (air emissions)
Incineration process (air emissions)
Residual waste
Energy and resource production/use
Electricity and CHP generation
Material reprocessing process and virgin material production
Bottom ash and filter dust (incineration process)

each scenario. Any energy consumed and recovered (Table 7) by the waste management system was assumed to be converted into natural gas, generating 3.82 kWh/m^3 of electricity and 22 MJ/m^3 of heat (estimated from data of KEMCO 2003) in CHP plants, except for energy consumption in landfill (diesel) and recovered and virgin paper processes (estimated from the LCI of a paper by the Japan Paper Association 2006—see Table 8).

Output categories for the LCI (refer to Fig. 1) were air emissions (23 categories: particulates, CO, nonfossil CO_2, fossil CO_2, CH_4, NO_x, N_2O, SO_x, HCl, HF, H_2S, total HCs, chlorinated HCs, dioxins/furans, ammonia, arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc), water emissions (28 categories: BOD, COD, suspended solids, total organic compounds, adsorbable organic halides, chlorinated HCs, dioxins/furans, phenols, aluminum, ammonium, total metals, arsenic, barium, cadmium, chromium, copper, cyanide, iron, lead, mercury, nickel, zinc, chloride, fluoride, nitrate, sulfide, sulfate, and phosphate), residual waste (waste volume: m^3 per ton waste, Table 9), and products (recovered energy, recovered materials, and compost produced).

This study considers carbon emissions from treating the biodegradable fraction of MSW, namely "nonfossil CO_2" emissions (refer to Table 3). Many forms of nonfossil sources of carbon present in the MSW stream represent main parts of carbon cycles; thus, they should be included in LCI because they are a part of the carbon life cycle of waste.

Adsorbable organic halides (AOX) are generated in the pulp and paper industry during the bleaching process. These compounds are formed as a result of a reaction between residual lignin from wood fibers and chlorine/chlorine compounds used for bleaching. Organic halides, including fluorine, chlorine, bromine, and iodine, can be carcinogenic. Chloroform was assumed to represent AOX in this LCI study (for example, emission factors: paper 1.72E−02, glass 2.87E−05, steel 1.30E−06, aluminum 5.60E−06, and HDPE 2.42E−02 kg/ton-waste in material recovery processes and paper 1.01E−02, glass 6.85E−05, steel 1.50E−01, aluminum 7.43E−01, non-HDPE 1.00E−01, and HDPE 1.50E−01 kg/ton-waste in virgin material processes). Various chlorinated HCs (chlorinated hydrocarbons, e.g., carbon tetrachloride and chloroform) are released into the atmosphere as solvents and refrigerants, among others, which react very slowly in the atmosphere. Phenol and 49 substituted phenols, sometimes called phenolics, are a class of chemical compounds consisting of a hydroxyl group (−OH) attached to an aromatic hydrocarbon group.

Table 7 Energy generation and natural gas equivalent for each scenario

Scenario	Landfill		Biological treatment		Incineration	
	LFG generation (Nm^3/ton)	Equiv. natural gas (m^3/ton)	Heat energy generation (MJ/ton)	Equiv. natural gas (m^3/ton)	Heat energy generation (MJ/ton)	Equivalent natural gas (m^3/ton)
S1	181	40.5[a]				
S2	135	30.2[a]				
S3	64	14.2[a]	350	8.7[b]		
S4	0	0.0	350	8.7[b]	3.3	0.08[c]

[a] 50% recovery from LFG

[b] 100% recovery from biogas

[c] Excluding the 2.3-MJ/ton incinerated waste used in the incineration process

Table 8 Process energy requirements analyzed for paper production in 70% and 0% recycling rates

Recycling rate	Total (GJ/ton)	Natural gas	Diesel oil	Hard coal	Electricity	Renewable energy
70%	22.25	0.20	4.99	7.12	1.54	8.41
0%	27.84	0.43	5.49	2.63	1.22	18.07

TCE and pentachlorophenol represent chlorinated HCs and phenols in this LCI analysis, respectively, and were selected to link with conversion factors of LIME.

Land use data with respect to different MSW facilities are essential in assessing primary production and damages to biodiversity. As shown in Table 10, space per ton waste in landfills was 0.0652 m^2, which was 10 times greater than other MSW facilities, including recyclables reprocessing facilities, biological treatment plants, and incineration plants.

3.2 Conversion factors on midpoints and endpoints

The emission factors in the previous section were arranged into conversion factors (Yi 2009), using nine midpoints and four endpoints adapted from LIME model (version 2006). Environmental impact factors of midpoints are as follows (detailed units are in brackets): global warming (GWP 100, Global Warming Potential 100), ozone-layer depletion (ODP, Ozone-layer Depletion Potential), resource consumption (1/R, R: Ultimate Reserves), acidification (DAP, Deposition-oriented Acidification Potential), human toxicity (HTP, Human Toxicity Potential), ecotoxicity (ETP, Eco-Toxicity Potential), eutrophication (EPMC, Eutrophication Potential considered marine Material Circulation), photochemical oxidant creation (OCEF, Ozone Conversion Equivalent Factor), and waste (m^3, the volume of landfills characterized by waste volume and landfill area, Table 9, adapted from LIME).

Damage factors involve four safeguard subjects: human health (DALY), social assets (USD, US Dollar, recalculated from original units of Japan Yen at the rate of ¥100 to the USD), biodiversity (EINES), and primary production (NPP, in units of the mass of carbon per unit area per year, kg/m^2/year).

LIME addresses the resource consumption factors associated with biodiversity and primary production that are related only to hard coal. Therefore, only hard coal (not natural gas or diesel oil) was assumed to damage biodiversity and primary production. Biodiversity damage factors for land use are shown in Table 11; the factors were estimated from the land use factors in Table 10 and the LIME factor, 4.75E−10 (EINES/m^2—MSW disposal area). To calculate primary production damage factors from maintenance factors, four MSW facilities were assumed to be available for 50 years. The primary production damage factors for land use were estimated from the land use factors in Table 10, and maintenance and land use change factors in Table 11. Monetization factors (in units of USD) are shown in Table 12.

4 Results and discussion

4.1 LCIA through the midpoint approach

4.1.1 Global impacts

As shown in Fig. 2, the best performing scenario, in terms of global warming potential (in units of GWP), was S4, which combined L (only incombustibles), MR, BT, and I, with respect to both of system and net emissions. This was largely due to the significant decrease in methane emissions from mixed waste in landfills (in comparison with S3), which negated the increase in GWP from emissions of plastic combustion in S4. Avoided impacts from the LFG recovery of L contributed to a greater level of reduction in GWP than avoided impacts from biogas and the compost of BT and the heat energy recovery of I for the same waste composition.

The net effect of all GHG emissions, including carbon emissions from treating biodegradable fractions in L, BT, and I processes, was greater than those of GWP, reversing the rankings of S3 and S4. With respect to all GHG emissions (including nonfossil CO_2, see Fig. 5) at the global level, S3 was the most effective, followed by S4, S2, and S1.

The resource consumption (in units of 1/R) in both system and avoided impacts indicated large differences

Table 9 Landfill volume by MSW materials (m^3/ton)

Paper	Glass	Steel	Aluminum	Plastic	Food waste	Wood and other combustibles	Rubber	Incombustibles	Water sludge	Industrial waste
1.25	0.56	0.71	0.71	1.00	0.91	2.00	1.00	0.56	1.00	1.00

Table 10 Land use by MSW facilities

	Landfill site[a]	Reprocessing facility[b]	Biological treatment plant[c]	Incineration plant[d]
Land use (m^2/ton)	6.52E−02	7.12E−03	2.94E−03	3.33E−03

[a] Metropolitan landfills (1992~2044) in Korea; 2,300 million ton waste into 15 million m^2 of landfill site

[b] Shihwa National industrial complex in Korea; 16,000 m^2 space with treatment capacities of 68 tons of paper, 25 tons of plastics, 30 tons of glass, and 4 tons of steel can per day, assuming a 50-year operational lifespan

[c] Gangdong biological treatment plant in Seoul with 14,493 m^2 space for treating 270 tons of food waste per day, assuming a 50-year operational lifespan

[d] The average (range with 2.00E−03~4.27E−03 m^2 per ton waste) of four incineration plants, including the Gangnam, Mapo, Nowon, and Yangcheon waste-to-energy plants in Seoul, assuming a 50-year operational lifespan

between S1 and the others. With respect to the estimation of the amount of natural gas in CHP plants, the avoided impacts in forms of LFG recovery were more effective than those in forms of biogas (BT) and heat energy recovery (I). Finally, S1 (using L) was the poorest performer with respect to global impacts. Ozone-layer depletion has no impact under all scenarios.

4.1.2 Regional impacts

The results of regional impacts (Fig. 3) show that system impacts, particularly those from the MR process (followed by I processes), made significant differences to acidification (in units of DAP) impacts. However, acidification impacts through the avoidance of emissions from virgin materials were beneficial, negating the emissions from MR processes.

Human toxicity (in units of HTP) and ecotoxicity (in units of ETP) impacts from system emissions were dependent mainly on I processes (followed by MR processes). With respect to human toxicity (comparing the same waste composition), emissions from waste combustion (I) had an impact 3,000 times greater than that of LFG combustion (L). S3 and S4 performed particularly poor in terms of eutrophication (in units of EPMC) because of the waste processes of BT (biogasification and compost) generated large quantities of water emissions. The results of the author's thesis (Yi 2009) indicated that the eutrophication potential of L depends on organic fractions. However, the impacts from L in total figures were negligible.

The landfill scenario (S1) was the worst performer with respect to regional impacts for all categories except eutrophication. In terms of regional impacts, S2 using L and MR was evaluated to be the most effective system.

4.1.3 Local impacts

Photochemical smog, which is partly affected by urban-scale weather in a local area, is a significant factor in the evaluation of effects on human health and the environment. The photochemical oxidant creation (in units of OCEF) from the system emissions of I in S4 was clearly significant

Table 11 Land use factors in biodiversity and primary production by MSW facilities

MSW facility	Biodiversity damage (EINES/ton-waste)	Primary production damage		
		Maintenance (kg/m^2/year)	Land use change (kg/m^2)	Primary production (kg/ton-waste)
Landfill site	3.10E−11	7.28E−01[a]	5.80E+00[c]	2.76E+00
Reprocessing facility	3.38E−12	1.36E+00[b]	9.66E+01[d]	1.17E+00
Biological treatment plant	1.40E−12	1.36E+00[b]	9.66E+01[d]	4.84E−01
Incineration plant	1.58E−12	1.36E+00[b]	9.66E+01[d]	5.49E−01

[a] Landfill sites were assumed to be currently "other use" (in the land use categories of paddy fields, dry fields, fruit tree orchards, other orchards, forests, barren land, building sites, and transportation sites, and other use) for the maintenance aspect

[b] Sites for reprocessing facilities, biological treatment plants, and incineration plants were assumed to be currently "building sites" for the maintenance aspect

[c] Landfill sites were assumed to be previously "other orchards" and currently "other use" for the land use change aspect

[d] Sites for reprocessing facilities, biological treatment plants, and incineration plants were assumed to be previously "other orchards" and currently "building sites" for the land use change aspect

Table 12 Monetization factors for endpoints adapted from LIME model

Safeguard subjects	Unit	Factor
Human health	USD/DALY	9.70E+04
Social assets	USD/USD	1.00E+00
Biodiversity	USD/EINES	4.80E+10
Primary production	USD/kg	2.02E−01

in comparison with other waste management systems (Fig. 4).

The results of waste (in units of m^3, landfill volume) related to landfill space and lifespan suggest that no or less landfills would lead to better performance. S4 using L, MR, BT, and I was the most effective performer with 1.13E−01 m^3, which was significantly lower than 1.15E+00 m^3 in S1. From the local impacts point of view, the avoided impacts from energy and material recovery in each system were negligible.

4.1.4 Potential impacts

No study has clearly explained how these two anthropogenic impacts (Fig. 5, nonfossil CO_2 and energy consumption) contribute to climate change and the heat island effect. Emissions of MSW systems in previous impact studies have been those generated on-site in MSW treatment or disposal plants or off-site in energy production or resource mining and digging facilities. However, emissions of the nonfossil CO_2 (in units of CO_2 equivalent) occur on-site from waste management processes (L, BT, and I), particularly depending on waste combustion. There was a significant increase in the nonfossil CO_2 equivalent in S4, which resulted from the waste combustion process of I.

Energy consumption (in units of MJ of energy equivalent) in waste management systems occurs on-site, whereas that from avoided impacts occurs in energy and resource production areas. All of the scenarios, including MR, were evaluated as on-site large energy consumption systems.

4.1.5 Ranking of each scenario

Each scenario was ranked by using the LCIA results (in accordance with nine environmental impact categories, which were divided into global, regional, and local scales). Midpoint approach results have been expressed in different indices; thus, comparing scenarios that take into account all categorical impacts have been difficult. Therefore, this study compares the scenarios by ranking them. The scenarios were ranked in terms of the degree of their impact: 4 (outer), 3, 2, and 1 (inner). As shown in Fig. 6, S1 (L) had a strong inclination toward all impacts, except eutrophication and photochemical oxidant creation, whereas S2 (L and MR) had a weak inclination toward all impacts.

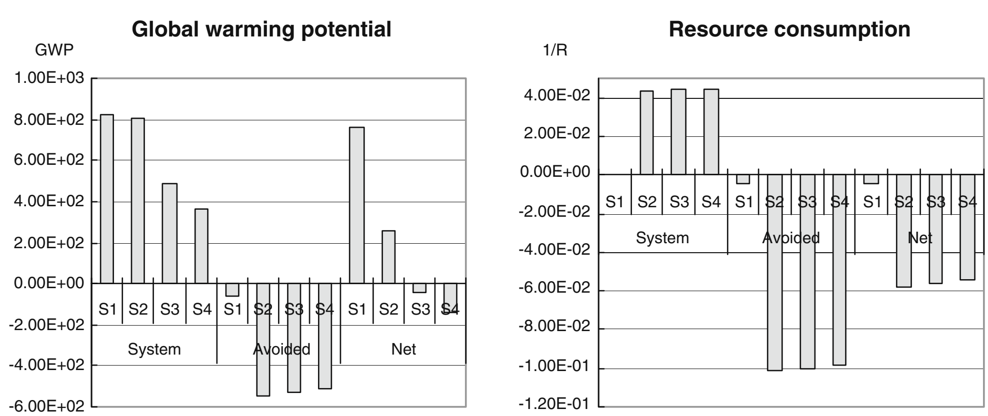
4.2 LCIA through the endpoint approach

4.2.1 Human health

Human health damages (in units of DALY) included global impacts caused by global warming, regional impacts by human toxicity, and local impacts by photochemical oxidation creation and urban air pollution (see Fig. 1).

In terms of local scales, the total MSW emissions in S2, which were mainly caused by the particulates, NOx, and SOx of the urban air pollution category, were attributed to 1.92E−04 DALYs (the graph of human health in Fig. 7) per person over a lifetime of 80 years, indicating that larger emissions were from MR processes. S4, the worst performing scenario with respect to damages from local impacts of MSW systems, represented 6,335 DALYs for the 24 million Seoul Metropolitan population in 2008, which corresponds to the average value of 2.63E−04 DALYs per person over a lifetime of 80 years. The

Fig. 2 Global impacts of MSW management scenarios



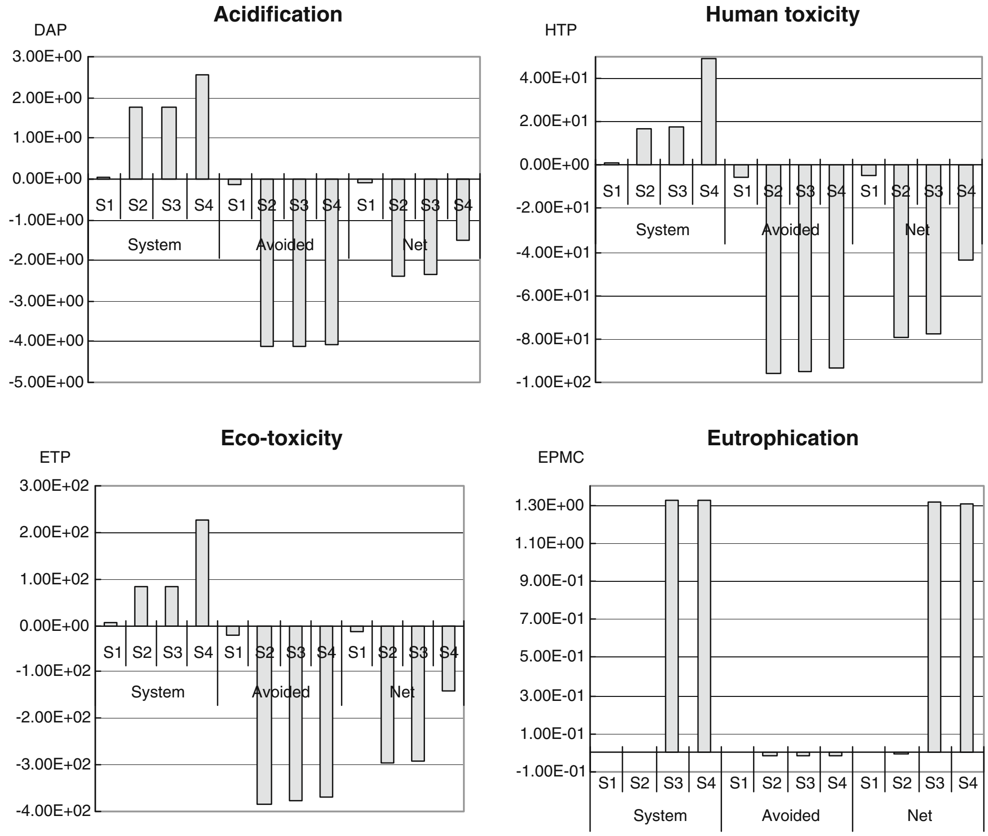


Fig. 3 Regional impacts of MSW management scenarios

outcomes of scenarios, including MR, indicate good practice through the avoidance of virgin material production impacts.

With respect to regional and local impacts arising from virgin material production, the DALY savings were significant enough to offset human health damages that were caused by material recovery processes. However, “local avoided impacts” included not only the damages to the Seoul Metropolitan area but also the damages to other areas and the country's local environment. Therefore, the actual avoided damages in Seoul would be less than the values shown in Fig. 7. Net emissions from global warming could be completely offset by adding BT, indicating negative outcomes. The net damage of S3 indicated best practice in human health and was mainly affected by urban air pollution on local scales.

4.2.2 Social assets

Social asset damages (in units of USD) resulted from global warming and resource consumption on global scales (zero damage from ozone-layer depletion), acidification and

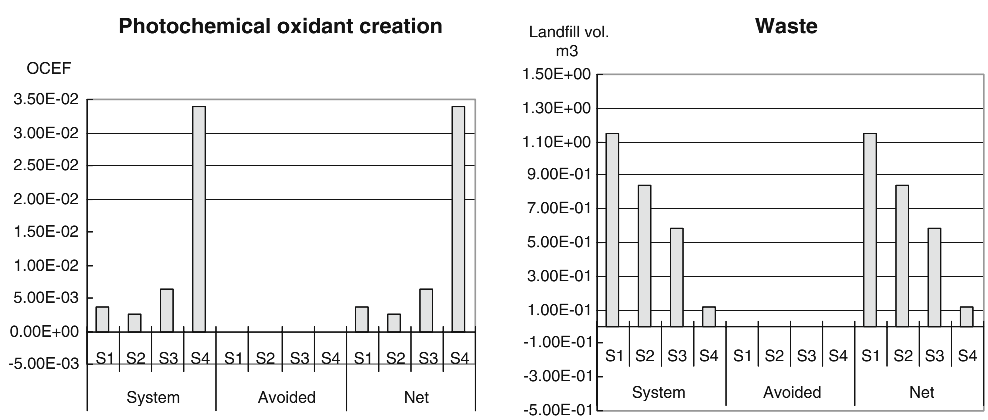
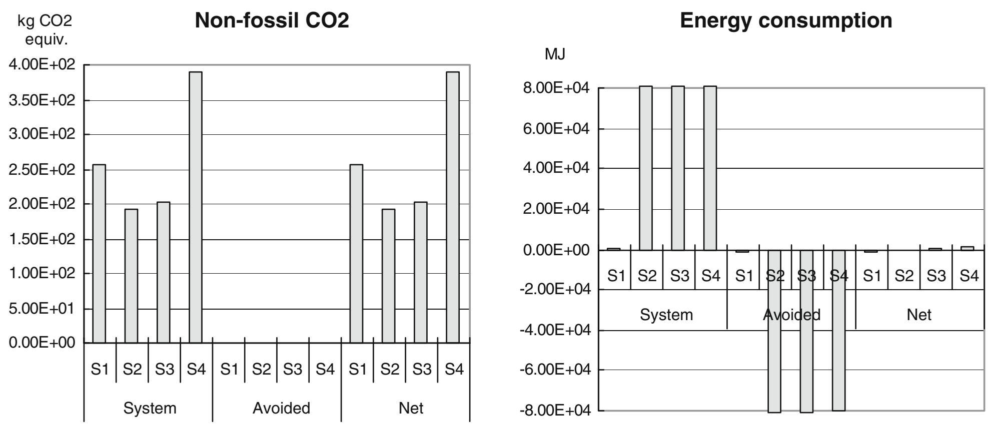


Fig. 4 Local impacts of MSW management scenarios

Fig. 5 Potential impacts of MSW management scenarios



eutrophication on regional scales, and photochemical oxidation creation on local scales.

There was a significant difference (the graph of social assets in Fig. 7) in the results of the other three damage analyses (i.e., human health, biodiversity, and primary production); social asset damages were caused mainly by global impacts. With respect to the damage analysis of system emissions, S1 showed a much lower level of regional damages than the other scenarios, demonstrating good agricultural/fish farming practice in local areas. In the detailed regional impact analysis of S3 and S4, the increases in graph bars indicating regional impacts were caused by the eutrophication of BT. Taking into account avoided impacts, the net damage of S2 was US \$−2.56, indicating best practice.

4.2.3 Biodiversity

Biodiversity damages, expressed as EINES, were caused by resource consumption at global scales, ecotoxicity at regional scales, and land use and waste at local scales.

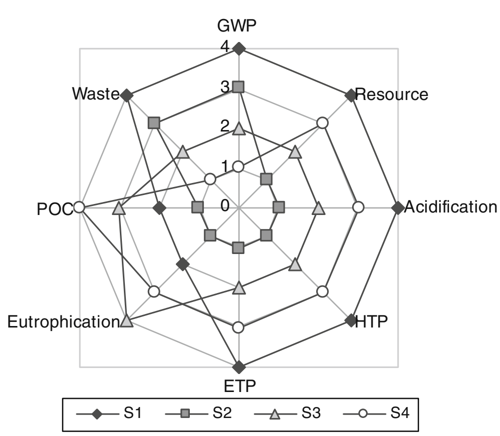


Fig. 6 Ranking of MSW management scenarios

As shown in the graph of biodiversity (see Fig. 7), S1 was influenced mainly by local impacts. This was due to the increased need for land use and waste (landfill volume) by MSW systems, including L processes. The observed data of MSW system emissions in S1 indicated that the biodiversity damage of the waste category was 1.28E−10 EINES per ton-waste, whereas that of the land use category was 3.10E−11 EINES per ton-waste.

The regional damage of MSW system emissions in S4 indicated bad practice in comparison to other scenarios. However, S4 represented the best practice with respect to the net biodiversity damages, even if the offset by avoided impacts on mainly regional and local scales would be less likely to occur off-site.

4.2.4 Primary production

In this primary production damage analysis (in units of kg-NPP per ton-waste), types of damages were assessed in terms of global impacts from resource consumption (zero damage from ozone-layer depletion), regional impacts from acidification, and local impacts from photochemical oxidation creation, land use, and waste.

In general, damages with respect to primary production were mainly influenced by global and local impacts (the graph of primary production in Fig. 7). The outcomes of scenarios with MR did not indicate good practice and contributed to global impacts only through resource consumption, particularly hard coal consumption. These data must be interpreted with caution because LIME addresses factors that are related only to hard coal. The life cycle inventories of paper recycling showed that the consumption of hard coal increased when recycling rates increased (see Table 8, 0% and 70%), indicating increased hard coal consumption and decreased black liquor production by paper recycling. The best system, S4, showed a positive (+, giving burden to the environment) result, which was different from the other endpoints.

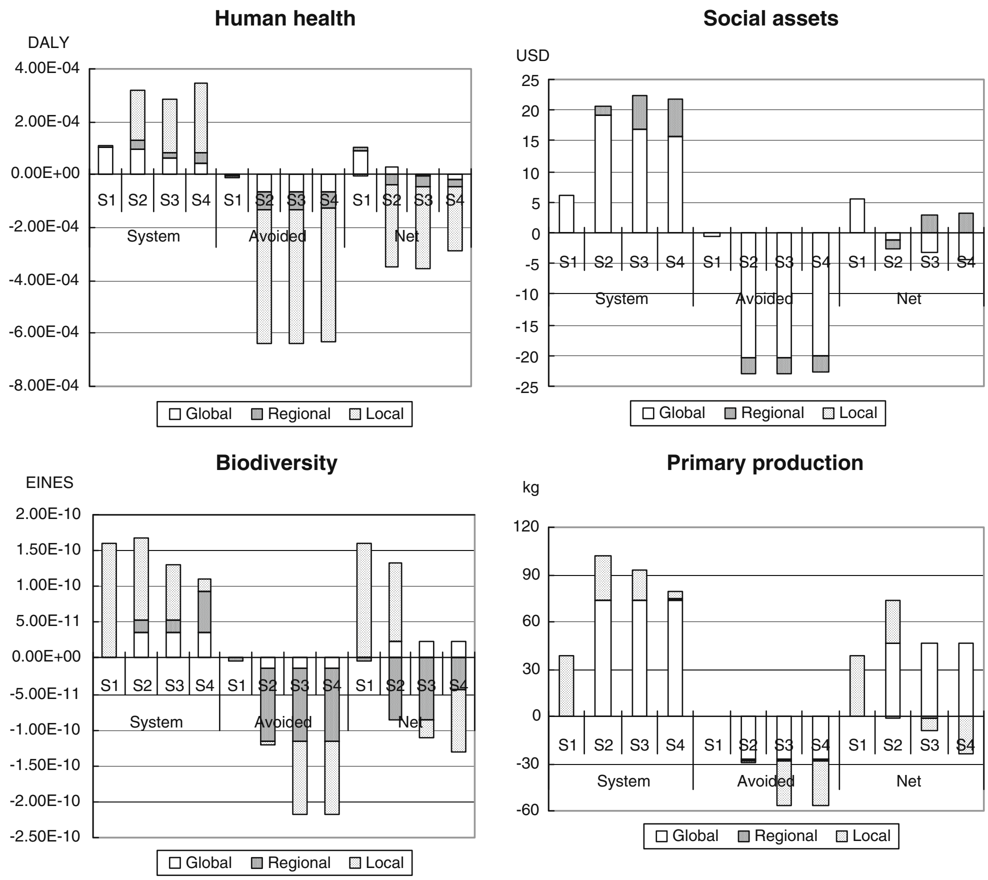


Fig. 7 Endpoint results of MSW management scenarios

4.2.5 Integration of estimated damages

S1 was the worst performer, with US $14.5 per ton-waste in terms of net global impacts mainly from human health and social asset damages. In contrast, the detailed data indicated S1 to be the best performer (except for biodiversity) in terms of system emissions. S4 was the best performer in terms of net global impacts.

With respect to regional impacts, S2 reflected best practice with US $9.2 saving (negative) per ton-waste. The positive graph bars of social asset damages in S3 and S4 were likely caused by eutrophication.

Noteworthy are the results of local impacts. There were significant differences between global and regional impacts with respect to their scales. S3 was the best performer with respect to local impacts, which was mainly due to human health damages. Human health damages of local impacts were mainly due to urban air pollution in this endpoint approach (unban air pollution category was omitted in the midpoint approach). The observed S2 data in LCIA on endpoints indicated that human health damages from urban air pollutions was −3.15E−04 DALYs, whereas that from photochemical oxidants was only −4.83E−08 DALYs. Thus, this method of scenario ranking provided results that were completely different from those of local impacts on midpoints (Fig. 8).

4.3 Differences of LCIA and interpretation with respect to midpoint and endpoint approaches

The observed data and scenario rankings in LCIA on midpoints and endpoints illustrate the differences in the LCIA results of the midpoint and endpoint approaches.

- By comparing the results of scenarios based on results of individual midpoint and endpoint categories, it would be possible to examine the effect of each impact category on

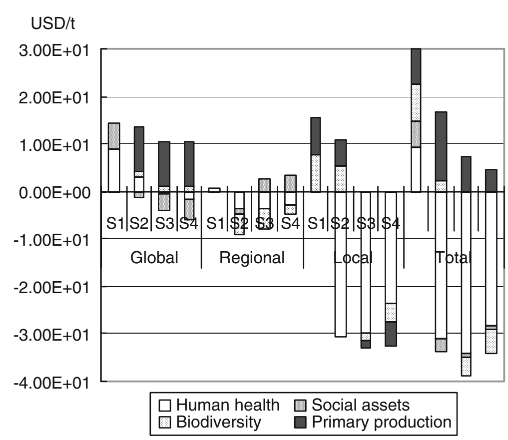


Fig. 8 Monetized damages of MSW management scenarios

Table 13 Main contributors influencing integrated results from the endpoint evaluation

Safeguard subjects	Spatial scale	Level of contribution by impact category		
		Main	Less	Much less
Human health	Global	Global warming		
	Regional	Human toxicity		
	Local	Urban air pollution		Photochemical oxidant creation
Social assets	Global[a]	Global warming		Resource consumption
	Regional	Eutrophication	Acidification	
	Local	Photochemical oxidant creation		
Biodiversity	Global	Resource consumption[b]		
	Regional	Eco-toxicity		
	Local	Waste	Land use	
Primary production	Global[a]	Resource consumption[b]		
	Regional	Acidification		
	Local	Waste, Land use	Photochemical oxidant creation	

[a] Ozone-layer depletion has no impact

[b] In terms of biodiversity and primary production, the conversion factor “resource consumption” is related only to hard coal, not to natural gas or diesel oil

four safeguard subjects (Table 13); the main contributors (i.e., the most significant impact category) had the greatest impact on integrated results of endpoints. If the endpoint categories included the only main contributor, the LCIA results of each endpoint for the scenarios were generally consistent with those of each midpoint. However, there were two exceptions: global-scale damages of biodiversity and primary production. This exception may be because the damage to biodiversity and primary production caused by resource consumption considered only that caused by hard coal, although resource consumption in the midpoint evaluation considered hard coal, natural gas, and diesel oil.

- The results changed dramatically when the main contributor was a new category not included in midpoint categories. For example, the local impacts of human health that included the urban air pollution and photochemical oxidant creation categories produced results for scenarios that were substantially different from those produced by the midpoint approach (or even the endpoint approach) that included only the photochemical oxidant creation category.
- The endpoint approach has a role in the integration of separate midpoints in the interpretation of LCIA. However, this should be interpreted with caution by considering what the contributors are composed of and how they are affected at each endpoint.

The key advantages of grouping impact categories are as follows:

- Simplification of midpoints: The midpoint approach, which includes many indicators, has been used as a tool in the detailed investigation of each process or holistic systems of MSW management. However, the approach has been limited in providing clear conclusions because of its many categories. The interpretation of midpoints could be simplified by grouping the many midpoint factors into global, regional, and local impact categories.
- Segmentation of endpoints: The endpoint approach, which includes simple indicators, has been helpful in the summarization of integration of interpretations. However, it has been limited in providing clear understanding with respect to damages linked from environmental impact categories at different spatial scales. Thus, the interpretation of endpoints could be segmented by grouping them into global, regional, and local scales.

5 Conclusions

In the midpoint approach, S1 using landfills was the worst performer in all but the waste (landfill volume) and photochemical oxidant creation categories. S2 using landfills and material recycling was evaluated to be an effective system in all impact categories except global warming and waste.

With respect to the global damage analysis, S1 was the worst performer in terms of human health and social assets, whereas S2, S3, and S4, which included material recycling, were poor performers in terms of biodiversity and primary production. With respect to all damage categories by

regional and local impacts in the endpoint approach, S1 was the worst performer in terms of human health, biodiversity, and primary production, whereas S4 was the worst performer in terms of social assets. S4 was the best performer in terms of damage at the global level, whereas S2 and S3 were the best at the regional and local levels, respectively.

With respect to the monetization analysis, S3 was "the most effective system" (US \$−31.6 per ton-waste, which is equivalent to US \$−1.29E+08 for total waste, e.g., 4,077,123 tons per year generated in Seoul City) in terms of the integration of all endpoints.

Any generalization of the study findings with respect to all environmental impact categories should be implemented with caution because these findings may not be transferable to best environmental practice. S3 in the midpoint approach did not demonstrate the best performance for any categories. The results of this study illustrate the differences in the LCIA outcomes with respect to the midpoint and endpoint approaches.

The LCIA results of each endpoint for the scenarios were generally consistent with those of each midpoint. However, the results changed dramatically when the main contributor was a new category not included in midpoint categories. In addition, it would be possible to interpret the effect of each indicator on safeguard subjects by integrating separate midpoints. The key advantage with respect to grouping impact categories in the midpoint and endpoint approaches can be described as "the simplification of midpoints and the segmentation of endpoints."

6 Recommendations and perspectives

This research raises many questions that warrant further research. This method does not provide an uncertainty evaluation of input data at the inventory level; it addresses only the main contributor for each impact category to four endpoints. One of the more significant findings is the spatial limitation of the damage offset by avoided impacts in terms of regional and local scales. Therefore, the current "net impact" research is limited by two different safeguard subjects exposed by on-site and off-site emissions. Risks arising from global environmental impacts could be offset regardless of on-site or off-site emissions. In this regard, future research is warranted to perform site-dependent impact assessment because there is a need to develop methodologies that would be better adapted to cover a wider range of situations and environmental and social conditions, particularly for the MSW system assessment.

In addition, it would be beneficial to investigate the suitability of midpoints and endpoints for different stakeholders with a low or high level of environmental expertise by comparing previous studies (Heijungs et al. 2003; Lenzen 2006). Much work is needed to compare social preferences of each scenario based on midpoint and endpoint interpretations to generate useful information for decision making purposes.

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